NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3731

TENSILE PROPERTIES OF INCONEL AND RS-120 TITANIUM-ALLOY SHEET UNDER RAPID-HEATING AND CONSTANT-TEMPERATURE CONDITIONS

By George J. Heimerl, Ivo M. Kurg, and John E. Inge

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Langley Field, Va.

Washington
July 1956

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SUMMARY

Results are presented of rapid-heating tests to determine the tensile strength of Inconel and RS-120 titanium-alloy sheet heated to failure at uniform temperature rates from 0.2° F to 100° F per second under constant load conditions. Yield and rupture stresses, obtained by rapid heating, are compared with yield and ultimate stresses from elevated-temperature tensile stress-strain tests for 1/2-hour exposure. The applicability of master curves and temperature-rate parameters to the prediction of yield and rupture stresses and temperatures under rapid-heating conditions was investigated.

INTRODUCTION

Most of the available data on the strength of materials at elevated temperatures are limited to constant-temperature conditions. In order to meet the need for information on the strength of missile and high-speed aircraft structural materials under rapid-heating conditions, a number of investigations have been made on aluminum and titanium alloys, steels, and high-temperature alloys heated to failure at high temperature rates under constant load (for example, ref. 1).

An investigation has also been in progress at the Langley Aeronautical Laboratory to determine the tensile properties of some structural materials heated to failure at relatively low temperature rates. The results for 7075-T6 and 2024-T3 aluminum-alloy sheet heated at rates from 0.2° F to 100° F per second under constant load are given in reference 2. Preliminary data on Inconel and RS-120 titanium-alloy sheet may be found in reference 3.

The present paper gives the final results of the rapid-heating tests of Inconel and RS-120 titanium-alloy sheet heated to failure at uniform temperature rates from 0.2° F to 100° F per second under constant-tensile-load conditions. Comparisons are made with conventional elevated-temperature tensile properties, and the possibility of predicting yield and rupture temperatures with temperature-rate parameters is investigated.

MATERIAL AND SPECIMENS

The Inconel and RS-120 titanium-alloy sheets were received and tested in the annealed condition. The chemical composition and tensile properties of the 0.064-inch-thick sheet materials, as reported by the manufacturers, are given in tables 1 and 2, respectively.

The rapid-heating and tensile stress-strain specimens were cut from the sheet with the longitudinal axis of the specimen taken parallel to the rolling direction. The dimensions of the specimens are given in figure 1. The rapid-heating specimen was modified slightly from that shown in figure 1 of reference 2 in order to help eliminate the tendency for rupture to occur outside the gage-length region. This was accomplished by reducing the specimen width slightly in the center region by grinding off about 0.015 inch from each edge over a 3-inch length.

TEST PROCEDURE

In the rapid-heating tests, the specimen was first loaded to the desired stress level by a dead-weight loading system and then heated at a constant temperature rate until failure occurred. Heating was accomplished by passing a large electric current directly through the specimen. Strains were measured over a 1-inch gage length by two linear variable transformer gages connected to the specimen through lever arms and gage frames. The equipment, test procedures, and method of analysis were essentially the same as those described in reference 2 with the following exceptions:

Preliminary tests of Inconel and RS-120 titanium-alloy sheet revealed a pronounced tendency for hot spots to develop at the narrowest point of the specimen for even very slight amounts of taper and for cold spots to occur at the thermocouple clamp and gage-point locations. These effects were mainly caused by the low thermal conductivities of these materials and were not present to the same extent in the case of the aluminum alloys which had conductivities about ten times larger than Inconel or RS-120 titanium alloy. Consequently, the specimen shape was modified slightly as previously described; peened thermocouples were employed instead of clamped thermocouples; and the strain-gage frames were redesigned.

In order to eliminate the cooling effect of the thermocouple clamp, No. 30 chromel-alumel thermocouples were peened carefully into closely fitted holes drilled halfway through the thickness of the specimen. Near the end of the test program, the thermocouples were spotwelded to the specimen with a spotwelder designed for this purpose. The spot-welded thermocouples gave more consistent results, in general, than the peened thermocouples because there was no tendency for them to loosen during the test and because the installation technique was not so critical. With proper installation, the response rate obtained with the peened thermocouples was about the same as that obtained with the spot-welded thermocouples. If the installation was imperfect, however, the response rate was considerably lower for the peened thermocouples.

In order to reduce the cooling effect of the extensometer gage frames (see fig. 4 of ref. 2), the frames were redesigned to reduce their mass and contact area. In the revised design, the knife edges were constructed of thin heat-treated Inconel X sheet. Each knife edge was ground to provide specimen contact at two points instead of over two finite lengths as before. The new gage frames are shown in figure 2 mounted in position on a specimen. Temperatures were markedly more uniform in the gage-length region when these new frames were used.

Conventional tensile stress-strain tests were run for comparative purposes. The specimens were exposed for 1/2 hour to the test temperature before loading at a strain rate of 0.002 per minute. The specimens, equipment, and procedure are the same as those described in reference 4. Some additional tests were also run with two peened thermocouples at the center of the specimen in place of the clamped thermocouples ordinarily employed in order to determine the effect of peening on the strength of the specimen.

TEST RESULTS AND DISCUSSION

Stress-Strain Tests

The elevated-temperature tensile properties of Inconel and RS-120 titanium-alloy sheet, exposed 1/2 hour and tested at a strain rate of 0.002 per minute, are given in tables 3 and 4, respectively, and are illustrated in figures 3 to 6.

Representative tensile stress-strain curves for these materials are shown in figure 3. The results for Inconel are characterized by irregular wavy curves in the plastic region which are associated with nonuniform plastic flow such as may occur when Lüders' lines develop. (Various aspects of the nature of inhomogeneous plastic strain, including Lüders' lines, are covered in ref. 5.) For a strain rate of 0.002 per minute, strain-hardening effects are small, in general, for strains up to about 1/2 percent; at 1,400° F, softening or relaxation effects predominate just after the material becomes plastic. The stress-strain curves for RS-120 titanium alloy, on the other hand, are smooth and show appreciable strain-hardening in the early plastic region except at 1,000° F.

The decrease in yield and ultimate stress with temperature for Inconel and RS-120 titanium-alloy sheet is indicated in figures 4 and 5. Two peened thermocouples, located at the midposition of the specimen to simulate rapid-heating test conditions, had little effect on the yield or tensile ultimate stress for Inconel except at temperatures below 1,000° F where the ultimate stress was reduced about 4 percent by peening. (See dashed curves of fig. 4.) The effect of peened thermocouples on the strength of specimens of RS-120 titanium alloy was investigated only at 80° F and the results were inconclusive. (See table 4.) Although the data are limited, the effect of peening in reducing the ductility appeared to be pronounced for both materials. (See elongation in tables 3 and 4.)

The reduction in Young's modulus with temperature is shown in figure 6 for both materials. The data on Inconel are limited but agree well with results given in reference 6 up to about 800° F. At higher temperatures, the results shown in figure 6 are somewhat higher than those of reference 6. The data on RS-120 titanium alloy are more extensive but show considerable scatter. The modulus curve for this material gives the average results obtained herein.

Rapid-Heating Tests

Results of the rapid-heating tests are given in table 5 and figures 7 to 10 for Inconel and in table 6 and figures 11 to 13 for RS-120 titanium alloy. Average coefficients of thermal expansion for these materials, based on the tests at 0.4 ksi, are listed in table 7.

Inconel.- Strain-temperature histories for the individual tests of Inconel sheet at three stress levels and temperature rates from 0.2° F to 100° F per second are illustrated in figure 7. The strains are total strains which include the elastic, thermal, and plastic strains. At 4 and 16 ksi, the results are regular in pattern and similar to those obtained for 7075-T6 aluminum alloy (ref. 2). At 28 ksi, however, the curves are discontinuous in the plastic region, sudden plastic flow occurring after intervals of elastic action. Similar plastic flow occurred at 25 ksi and 32 ksi. These irregular lines are also apparently the consequence of nonuniform plastic flow previously noted with regard to the stress-strain tests. Yield temperatures are indicated by the tick marks which are offset 0.2 percent from the calculated elastic-strain and thermal-expansion curve. Values of the moduli employed in these calculations are the same as those shown in figure 6 except that slightly greater values were taken for RS-120 titanium alloy above 600° F in order to obtain a better fit with the test results. There appears to be some indication from these and other tests that elastic stress moduli under rapid-heating conditions may be somewhat greater in the upper temperature region for the material than the static values obtained from stress-strain tests. The calculated curves are in good agreement in the elastic region with the test curves at each stress level.

The logarithmic nature of the increase in yield and rupture temperatures with temperature rate is shown in figure 8. The relationship is approximately linear as indicated by the test points and the solid lines. This linearity is consistent with the results obtained for the aluminum alloys (ref. 2) and for a low carbon steel (ref. 7).

Yield stresses obtained under rapid-heating conditions are compared with the elevated-temperature tensile stress-strain results in figure 9. The rapid-heating curves for the nominal temperature rates were obtained from the experimental curves of figure 8 which were extrapolated where required. Above 1,000° F, the rapid-heating results for rates above about 2° F per second are greater at a given temperature than those obtained from the tensile stress-strain test for 1/2-hour exposure. Below 1,000° F, the rapid-heating results are lower than those from the stress-strain test. A possible explanation may be found in an examination of the strain-temperature curves for 28 ksi in figure 7 in which it is evident that yield temperatures would be higher if premature abrupt plastic flow had not occurred.

A similar comparison between the rupture stress obtained from the rapid-heating test and the tensile ultimate stress obtained from the tensile stress-strain test is given in figure 10. The rapid-heating results are considerably greater than the tensile stress-strain results for 1/2-hour exposure except in the case of very low temperature rates.

<u>RS-120 titanium alloy</u>.- Illustrative strain-temperature curves for individual tests of RS-120 titanium-alloy sheet at three stress levels and temperature rates from 0.2° F to 100° F per second are shown in figure 11. The pattern of the results is different at each stress level. The banding together of the curves below yield at 50 ksi and the irregular behavior above yield at 75 ksi are similar in some respects to the behavior of 2024-T3 aluminum alloy (ref. 2), which is an age-hardenable material. These results indicate that the strength of RS-120 titanium alloy could probably be altered by heat treatment.

Experimental yield and rupture temperatures plotted against the temperature rate on a logarithmic scale are shown in figure 12. Yield temperatures increase approximately linearly with the logarithm of the temperature rate except at 50 and 60 ksi. Rupture temperatures also increase with the temperature rate except at 75 ksi; the results are approximately linear over most of the entire range.

The rapid-heating and tensile stress-strain results are compared in figure 13. The solid or rapid-heating curves for arbitrary temperature rates from 0.2° F to 100° F per second were constructed by means of the experimental curves of figure 12. Yield stresses obtained under rapid-heating conditions are greater for a given temperature than the tensile yield stress for 1/2-hour exposure for rates above 2° F per second except in the vicinity of 700° F. Rupture stresses under rapid-heating conditions are appreciably greater at a given temperature than the tensile ultimate stress for 1/2-hour exposure for rates above 0.2° F per second.

Master yield and rupture stress curves.- Master yield and rupture curves for Inconel and RS-120 titanium alloy (figs. 14 and 15, respectively) were constructed by means of linear temperature-rate parameters derived by the method described in reference 2. For Inconel, the parameter is

$$\frac{T - 250}{\log h + 13} \tag{1}$$

For RS-120 titanium alloy, the parameter is

$$\frac{T + 800}{\log h + 23} \tag{2}$$

For these parameters, T is either the yield or rupture temperature in $^{\circ}$F and h is the temperature rate in $^{\circ}$F per second. The stresses in figures 14 and 15 are those at which yield or rupture temperatures occur.

For Inconel (fig. 14), the correlation of the data with the master curve is good for both yield and rupture. Consequently, yield and rupture stresses or temperatures may be readily determined for different temperature rates by means of the parameter. In order to show the accuracy with which this may be done, calculated yield and rupture temperatures are compared with the test results in figure 8. The agreement is fairly close for both yield and rupture temperatures except for some occasional scatter.

For RS-120 titanium alloy (fig. 15), the correlation of the data with the master curves for yield and rupture is poor except at a few stress levels. At 50 and 60 ksi for yield and 75 ksi for rupture, no correlation was obtained. This lack of correlation for yield and rupture at these stress levels was expected, however, in view of the nature of the results. (See fig. 12.) The poor correlation is further emphasized in figure 12 by the comparisons shown between yield and rupture temperatures and the curves calculated by means of parameter (2). The master curves shown in figure 15 for this material are of limited value and can be applied with some degree of assurance only in the regions where they are solid.

CONCLUDING REMARKS

When Inconel and RS-120 titanium-alloy sheet are heated at temperature rates from 0.2° F to 100° F per second, yield and rupture stresses may be somewhat less or appreciably greater than the corresponding tensile yield or ultimate stresses obtained from the stress-strain test for 1/2-hour exposure and strain rate of 0.002 per minute, depending upon the temperature rate. In general, yield and rupture temperatures for these materials increase with the logarithm of the temperature rate with the exception of the titanium alloy at certain stress levels. Except for discontinuous plastic flow in one stress region, the strain-temperature results for Inconel were regular in pattern. The behavior of the titanium alloy was markedly irregular at a number of stress levels.

Yield and rupture stresses and temperatures for Inconel can be satisfactorily predicted by means of a master curve and temperature-rate parameter. This was not the case for RS-120 titanium-alloy sheet because of its irregular behavior. A temperature-rate parameter was found to be applicable only in certain regions for this material.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 16, 1956.

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TABLE 1

CHEMICAL COMPOSITION

[In percent]

Material	C	Mn	Si	S	Fe	Cr	Ni	N	Cu	Ti
Inconel*	0.08	0.25	0.25	0.007	7.0	15.0	77.0	------	0.2	------
RS-120** titanium alloy	0.106	5.70	----	------	---	----	----	0.022	---	94.17

*Obtained from reference 6.
**Information on this heat of material obtained from Republic Steel Corporation.

TABLE 2

LONGITUDINAL TENSILE PROPERTIES

Material	Condition	Young's modulus, psi	Ultimate stress, ksi	Yield stress, ksi	Elongation in 2 inches, percent
Inconel*	Annealed	31×10^6	90.5	36.5	47
RS-120** titanium alloy	Annealed	---------	133.0	121.3	14

*Obtained from reference 6.
**Information on this heat of material obtained from Republic Steel Corporation.

TABLE 3

TENSILE STRESS-STRAIN PROPERTIES FOR INCONEL SHEET

[1/2-hour exposure; strain rate of 0.002 per minute]

Temperature, °F	Yield stress, ksi (a)	Ultimate stress, ksi	Young's modulus, psi	Elongation in 2 inches, percent	Type of thermocouple attachment
80	36.4	92.4	31.8×10^6	44	None
	36.3	92.2	31.0	43	None
	37.1	88.1	30.2	29	Peened
1,000	26.2	82.4	26.4	46	Clamped
	26.4	78.4	23.1	33	Peened
1,400	19.1	26.3	21.4	--	Clamped
	18.8	25.6	22.7	44	Peened
1,800	5.2	8.0	13.4	--	Clamped
	5.3	8.6	13.7	44	Peened

[a]0.2 percent offset.

TABLE 4

TENSILE STRESS-STRAIN PROPERTIES FOR

RS-120 TITANIUM-ALLOY SHEET

[1/2-hour exposure; strain rate of 0.002 per minute]

Temperature, °F	Yield stress, ksi (a)	Ultimate stress, ksi	Young's modulus, psi	Elongation in 2 inches, percent	Type of thermocouple attachment
80	102.3	125.9	15.5×10^6	24.5	None
	103.9	126.8	15.5	24	None
	103.9	-----	14.2	21	None
	-----	126.6	15.7	8	Peened
	105.5	-----	14.8	7	Peened
	105.3	125.0	16.3	14	None
	103.1	125.0	18.3	16	None
200	83.0	-----	15.9	23	Welded
	85.8	111.0	14.6	20	Welded
400	66.5	-----	14.3	23	Clamped
	64.0	-----	13.4	24	Clamped
	64.2	96.6	15.3	--	Welded
	65.0	97.3	13.1	22	Welded
600	-----	-----	13.5	--	Welded
	59.0	88.4	12.6	20	Welded
	56.2	86.4	13.3	15	Welded
	56.5	88.5	11.8	17	Welded
800	-----	-----	11.4	--	Clamped
	44.8	59.9	10.4	22	Welded
	46.3	56.6	12.2	21	Welded
	43.4	59.5	9.7	25	Welded
1,000	13.3	15.1	6.0	66	Welded
	12.7	15.2	6.5	67	Welded

[a]0.2 percent offset.

TABLE 5

TENSILE PROPERTIES FOR INCONEL SHEET UNDER RAPID-HEATING CONDITIONS

Stress, ksi	Temperature rate, °F/sec	Yield temperature, °F	Rupture temperature, °F	Elongation in 2 inches, percent
4	0.2	1,695	Over 2,000	--
	2	1,860	Over 2,000	--
	20	1,984	Over 2,000	37
	100	[a]2,070	Over 2,000	--
10	2	1,596	1,867	37
16	2	1,467	1,744	--
	20	1,580	1,843	30
	100	1,623	------	25
22	2	1,394	1,626	29
	100	1,493	1,795	31
25	2	1,175	1,600	29
	95	1,209	1,805	29
28	0.2	662	1,460	--
	0.233	652	1,478	--
	2	716	1,548	27
	20	739	1,704	24
	96	770	1,748	29
32	2	319	1,500	30
50	2	------	1,270	27
	100	------	1,432	--

[a]Estimated. Recorder measured only to 2,000° F.

TABLE 6

TENSILE PROPERTIES FOR RS-120 TITANIUM-ALLOY SHEET

UNDER RAPID-HEATING CONDITIONS

Stress, ksi	Temperature rate, °F/sec	Yield temperature, °F	Rupture temperature, °F	Elongation in 2 inches, percent
15	2	1,017	------	--
	78	1,183	1,483	55
25	0.2	886	1,013	--
	2.2	948	1,068	--
	18	988	1,136	19
	96	1,074	1,251	26
42.5	0.2	733	------	--
	2	783	904	16
	15	865	1,055	18
	100	910	1,085	--
50	0.2	618	863	17
	2	610	950	11
	2	----	933	10
	20	572	1,013	12
	90	682	1,085	13
60	0.2	557	873	15
	2	536	925	14
	20	507	969	11
	77	569	1,092	15
68	0.2	350	810	13
75	0.2	239	763	14
	2	279	785	8
	20	323	766	7
	88	377	743	12

TABLE 7

THERMAL EXPANSION

Temperature range, °F	Thermal expansion strain*	Average coefficient of thermal expansion per °F
Inconel sheet		
80 to 200	0.0009	7.5×10^{6}
80 to 400	.0025	7.8
80 to 600	.0042	8.1
80 to 800	.0060	8.3
80 to 1,000	.0080	8.7
80 to 1,200	.0101	9.0
80 to 1,400	.0124	9.4
80 to 1,600	.0148	9.7
80 to 1,800	.0174	10.1
RS-120 titanium-alloy sheet		
80 to 200	0.00070	5.8×10^{6}
80 to 400	.00185	5.8
80 to 600	.00300	5.8
80 to 800	.00421	5.9
80 to 1,000	.00566	6.2
80 to 1,100	.00640	6.3

*From figure 7 for Inconel and figure 11 for RS-120 titanium alloy.

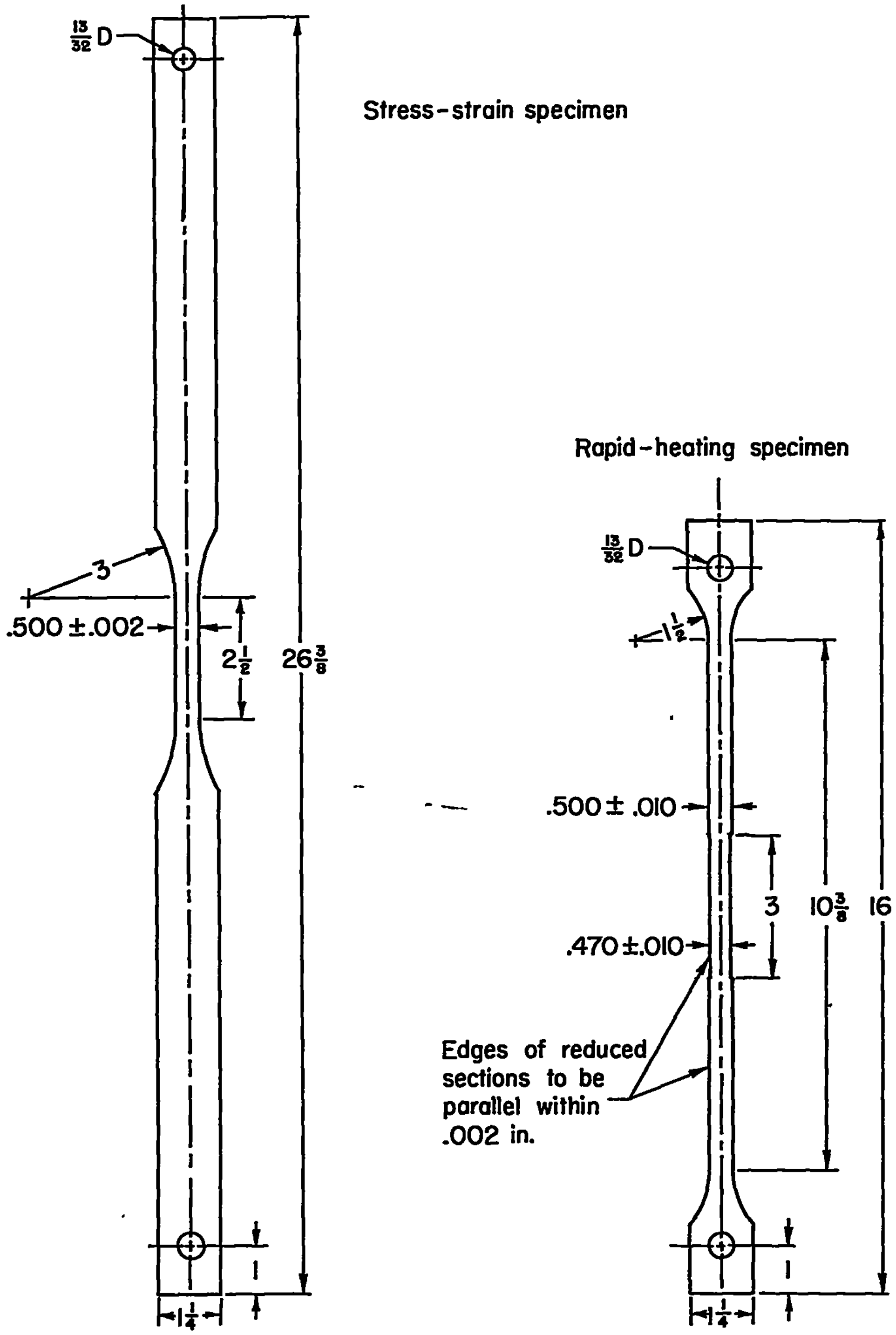

Figure 1.- Stress-strain and rapid-heating tensile test specimens. All dimensions are in inches.

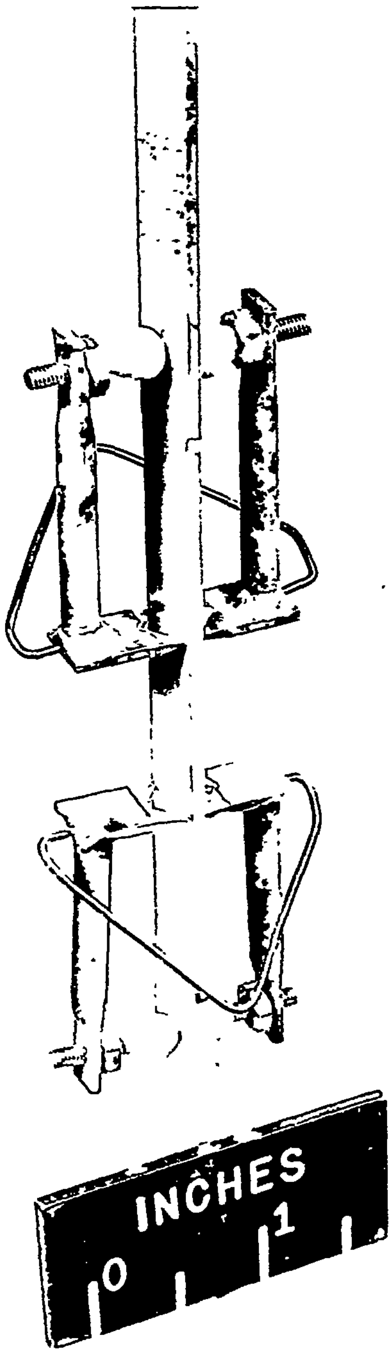

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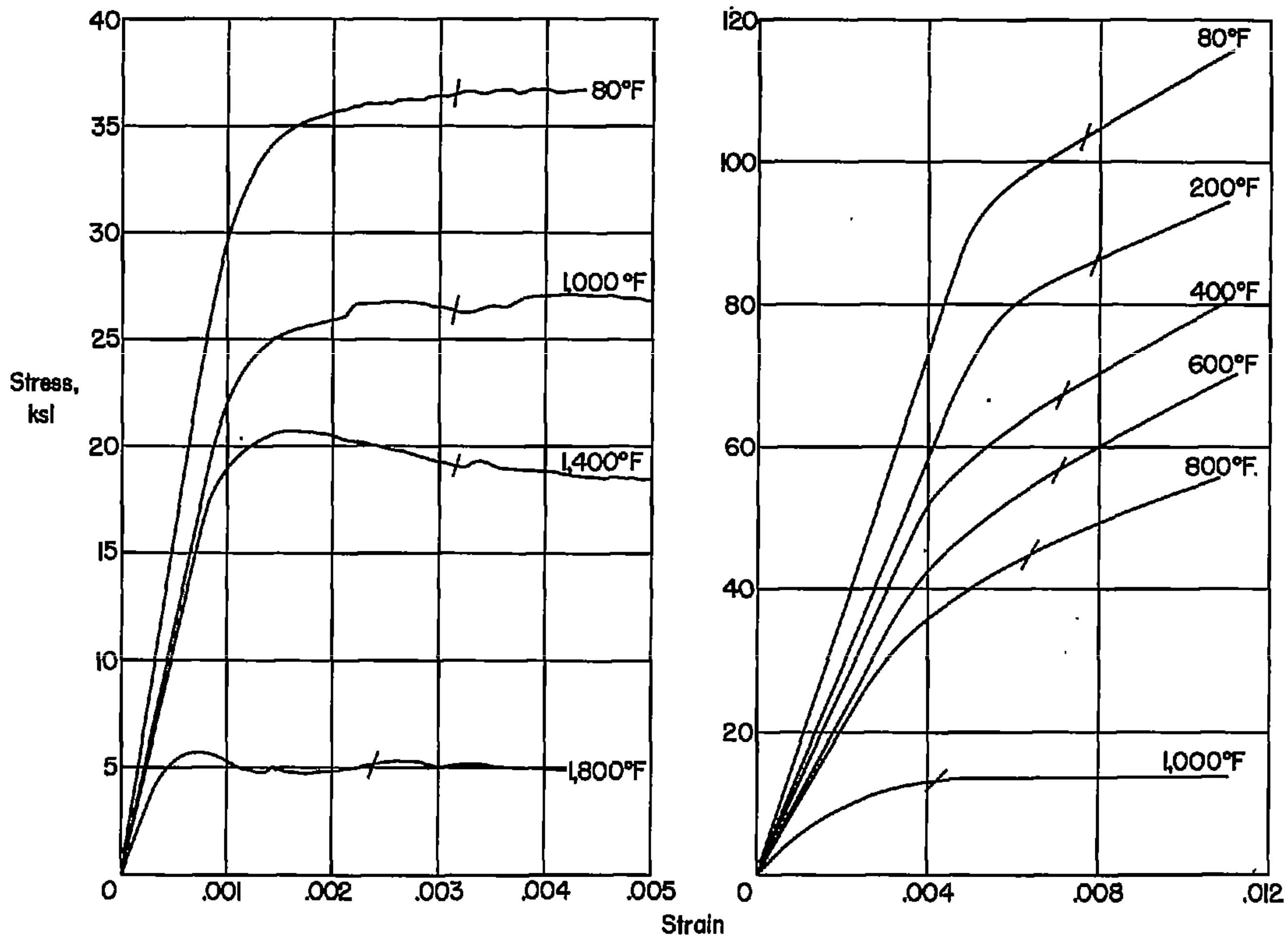
Figure 2.- Revised extensometer frames mounted on a test specimen.



(a) Inconel.

(b) RS-120 titanium alloy.

Figure 3.- Tensile stress-strain curves for Inconel and RS-120 titanium-alloy sheet after 1/2-hour exposure for a strain rate of 0.002 per minute. The tick marks indicate the 0.2-percent-offset yield stresses.

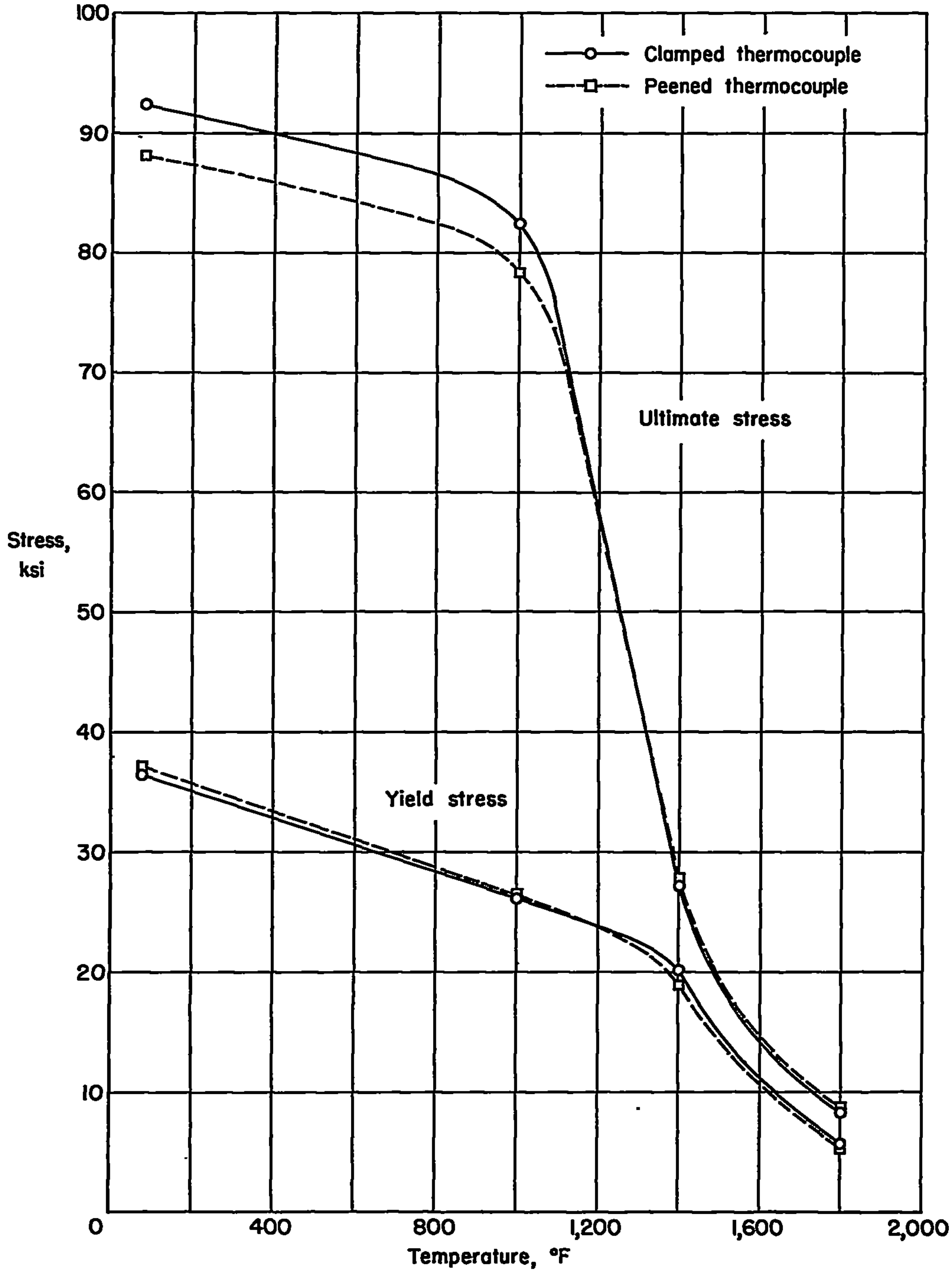


Figure 4.- Tensile yield and ultimate stresses for Inconel sheet at elevated temperatures after 1/2-hour exposure for a strain rate of 0.002 per minute. Yield stress is for 0.2 percent offset.

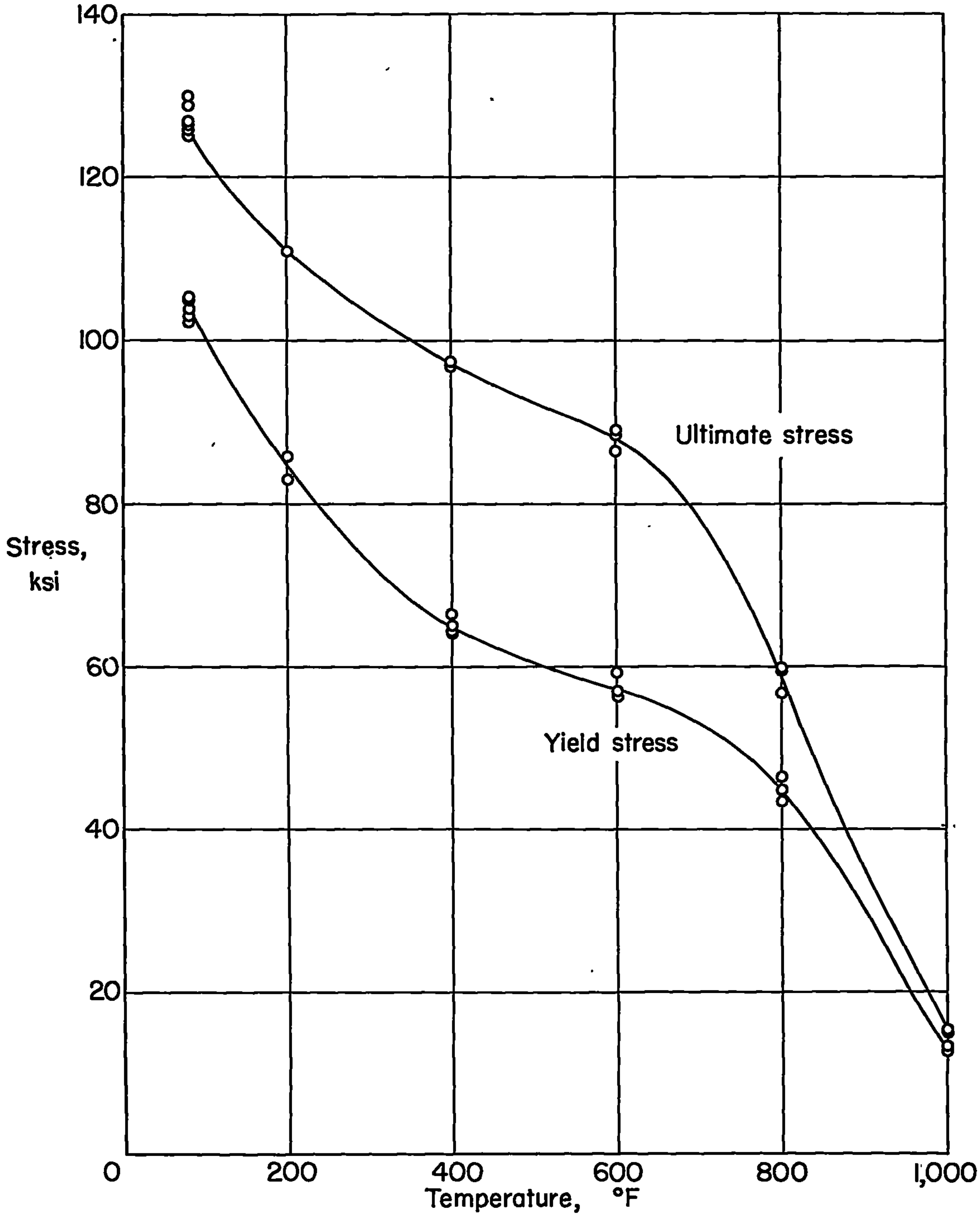


Figure 5.- Tensile yield and ultimate stresses for RS-120 titanium-alloy sheet after 1/2-hour exposure for a strain rate of 0.002 per minute. Yield stress is for 0.2 percent offset.

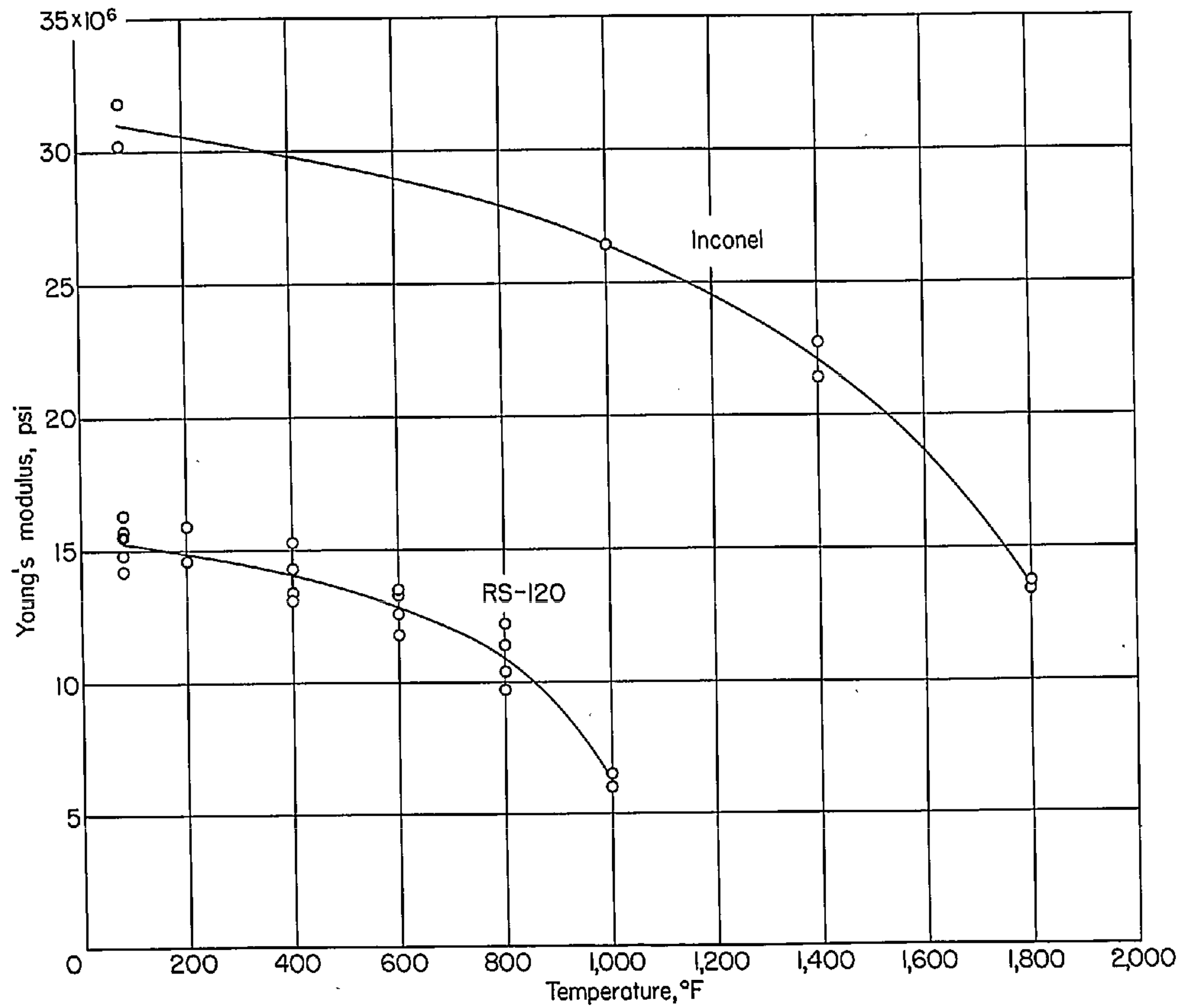


Figure 6.- Young's modulus for Inconel and RS-120 titanium-alloy sheet at elevated temperatures after 1/2-hour exposure.

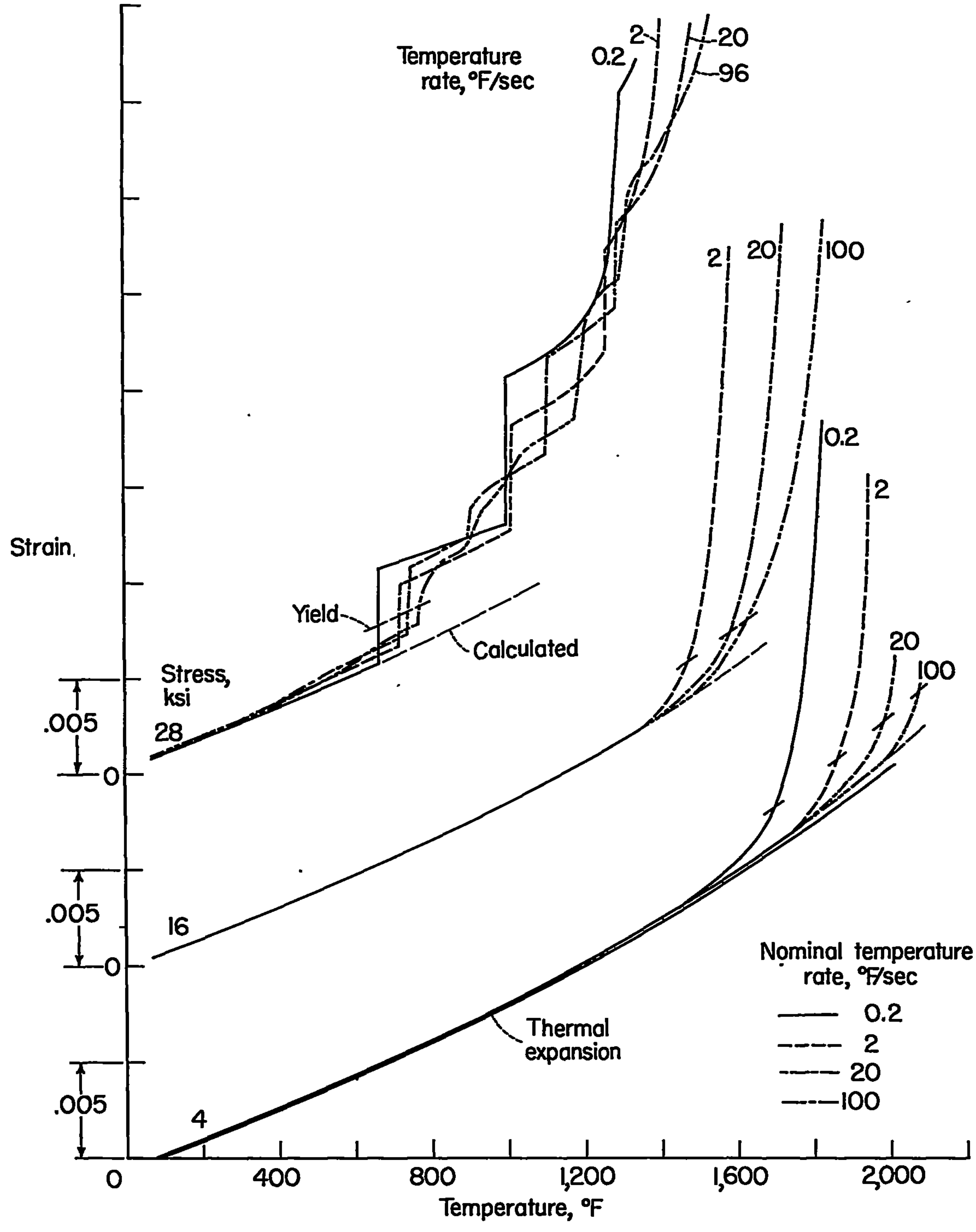
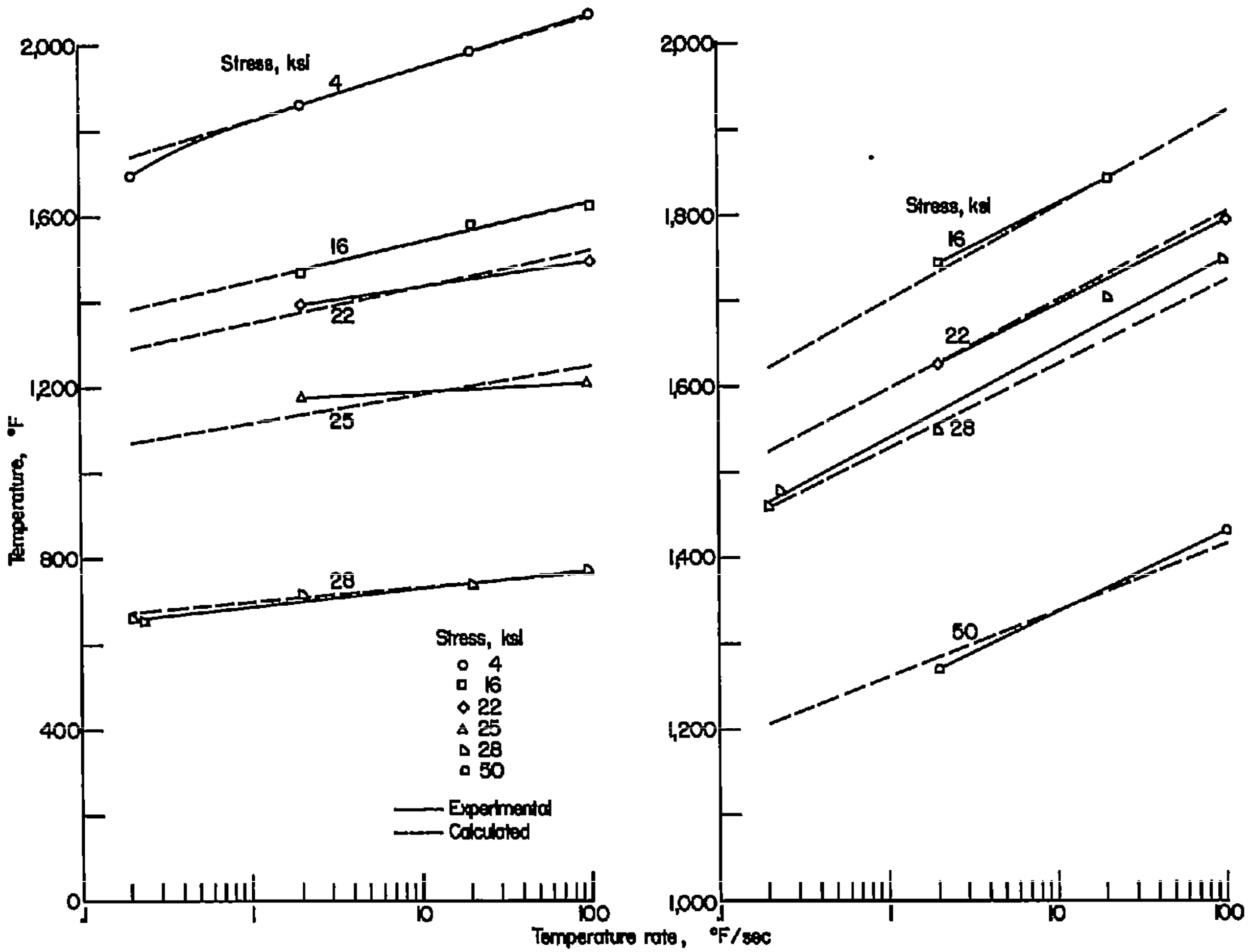


Figure 7.- Strain-temperature histories of Inconel sheet for temperature rates from 0.2° F to 100° F per second for various stresses.



(a) Yield. (b) Rupture.

Figure 8.- Experimental and calculated yield and rupture temperatures for Inconel sheet for temperature rates from 0.2° F to 100° F per second for various stresses.

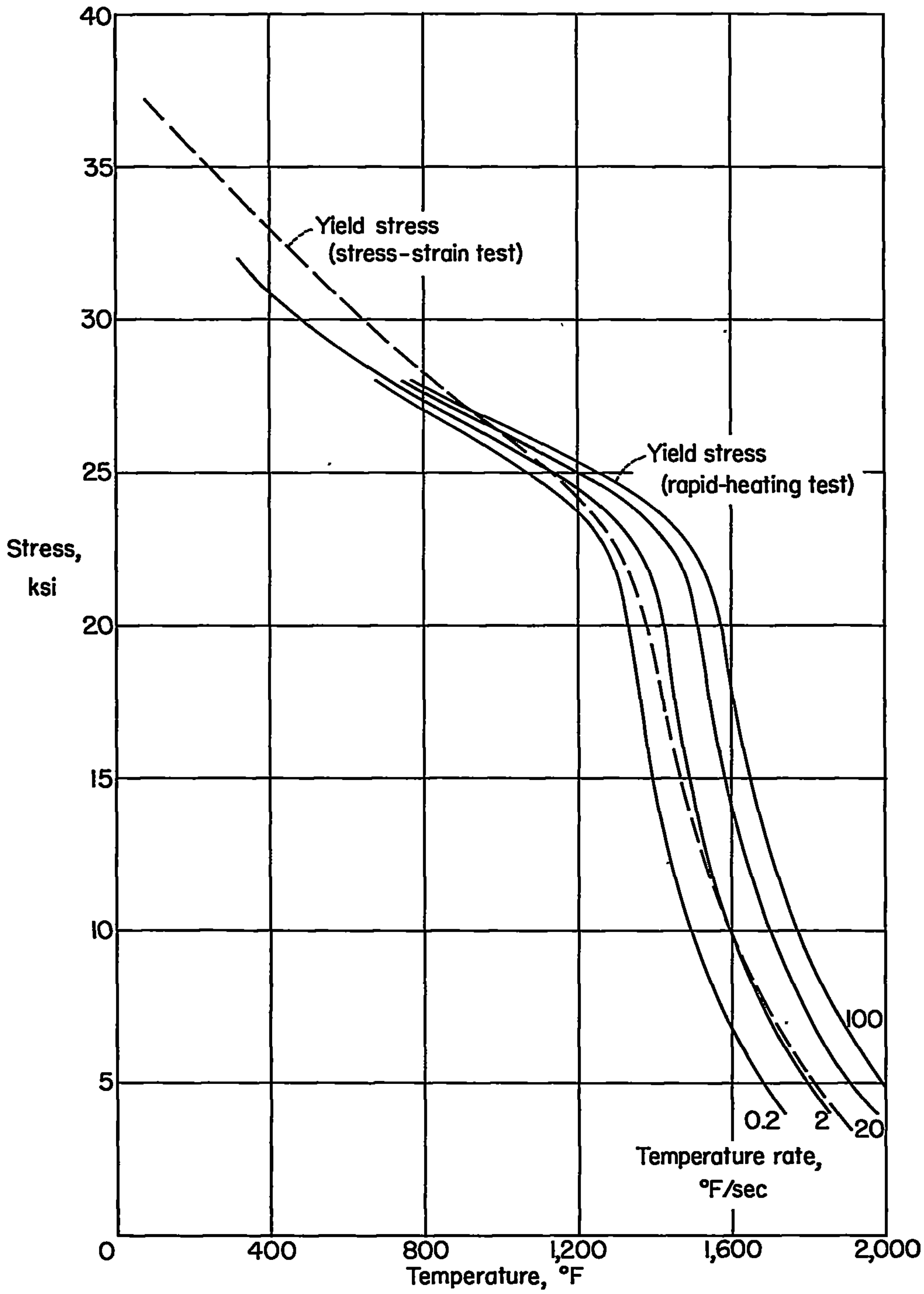


Figure 9.- Tensile yield stress of Inconel sheet for rapid-heating tests from 0.2° F to 100° F per second and for stress-strain tests after 1/2-hour exposure for a strain rate of 0.002 per minute.

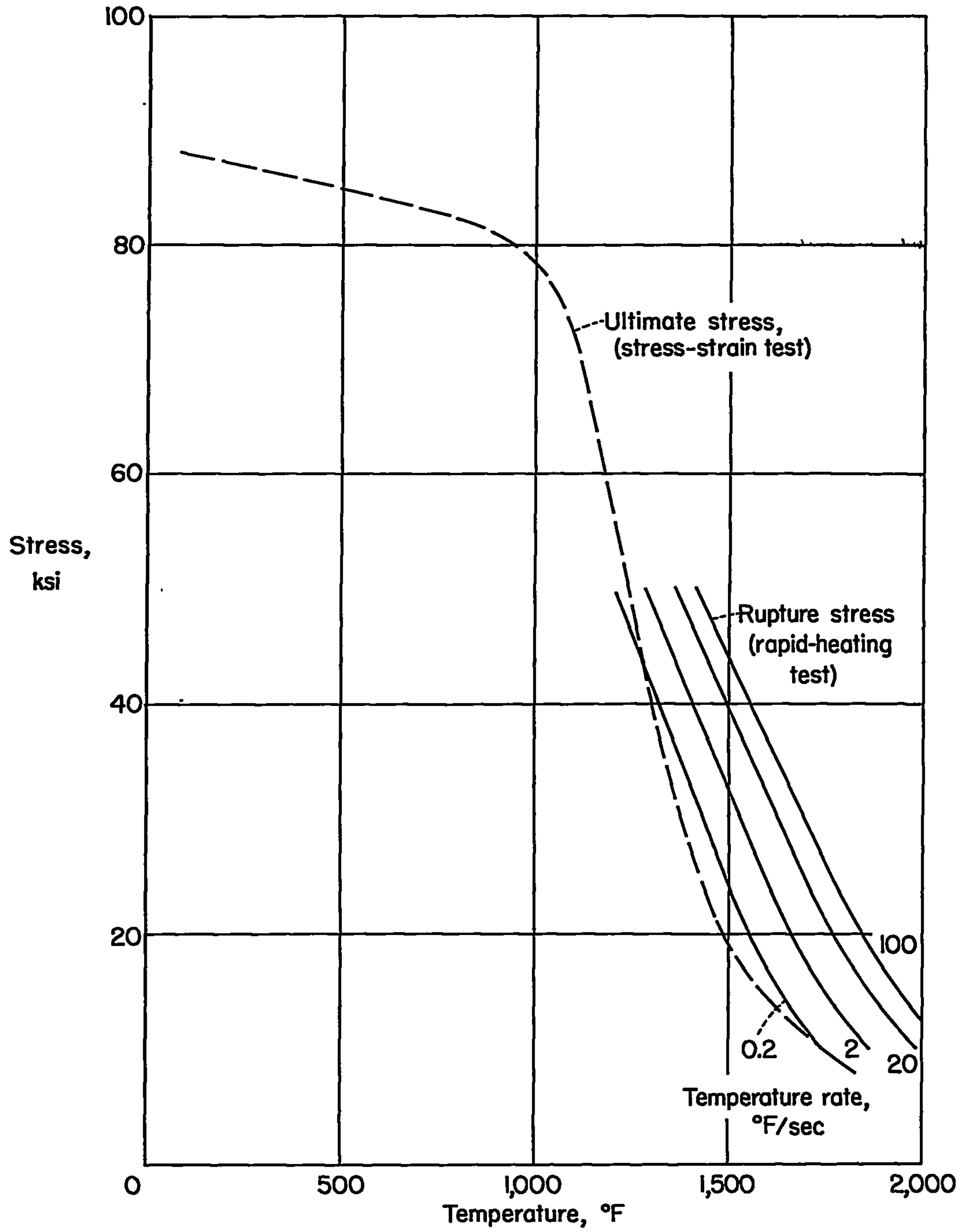


Figure 10.- Tensile rupture stress of Inconel sheet for rapid-heating tests from 0.2° F to 100° F per second and for stress-strain tests after 1/2-hour exposure for a strain rate of 0.002 per minute.

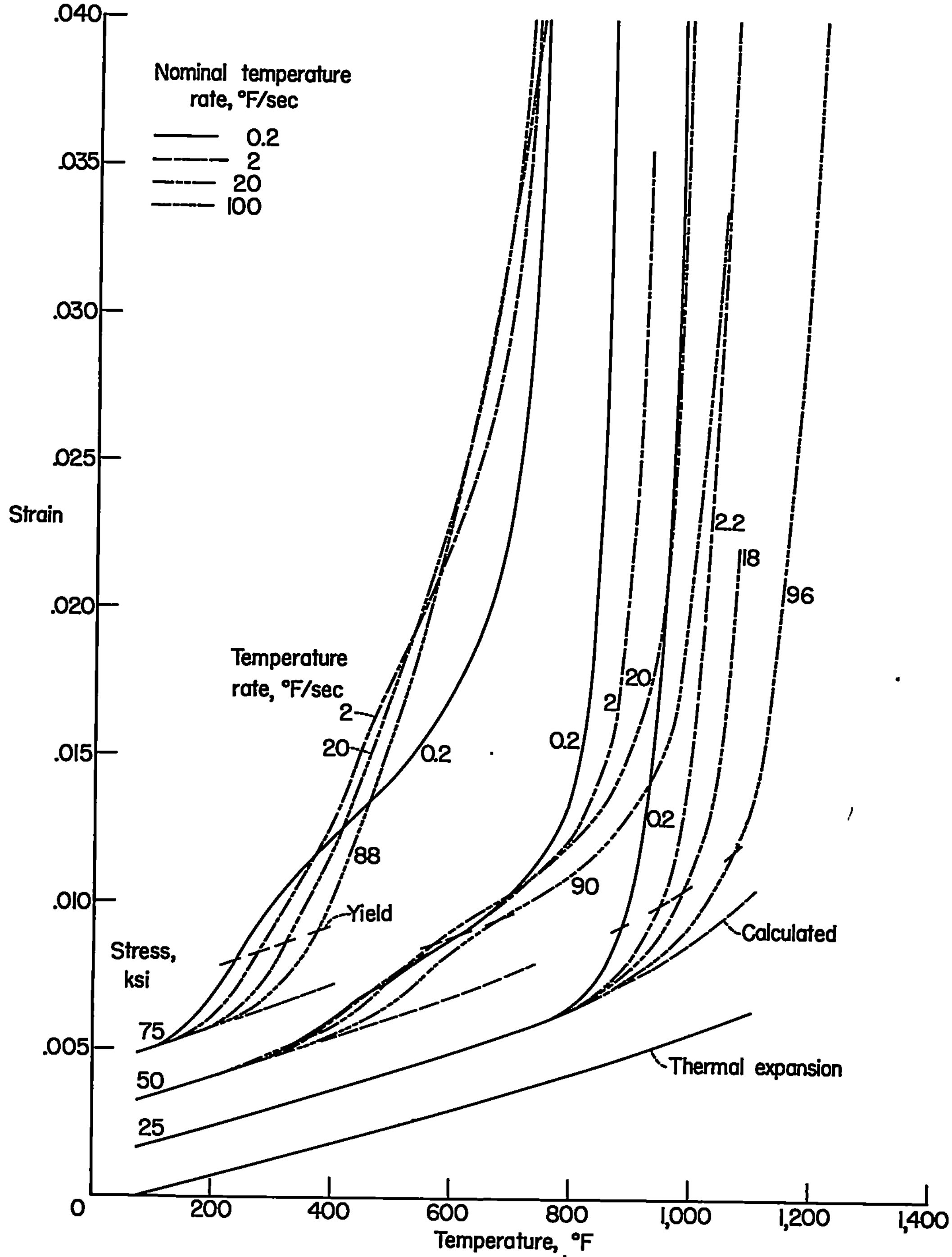
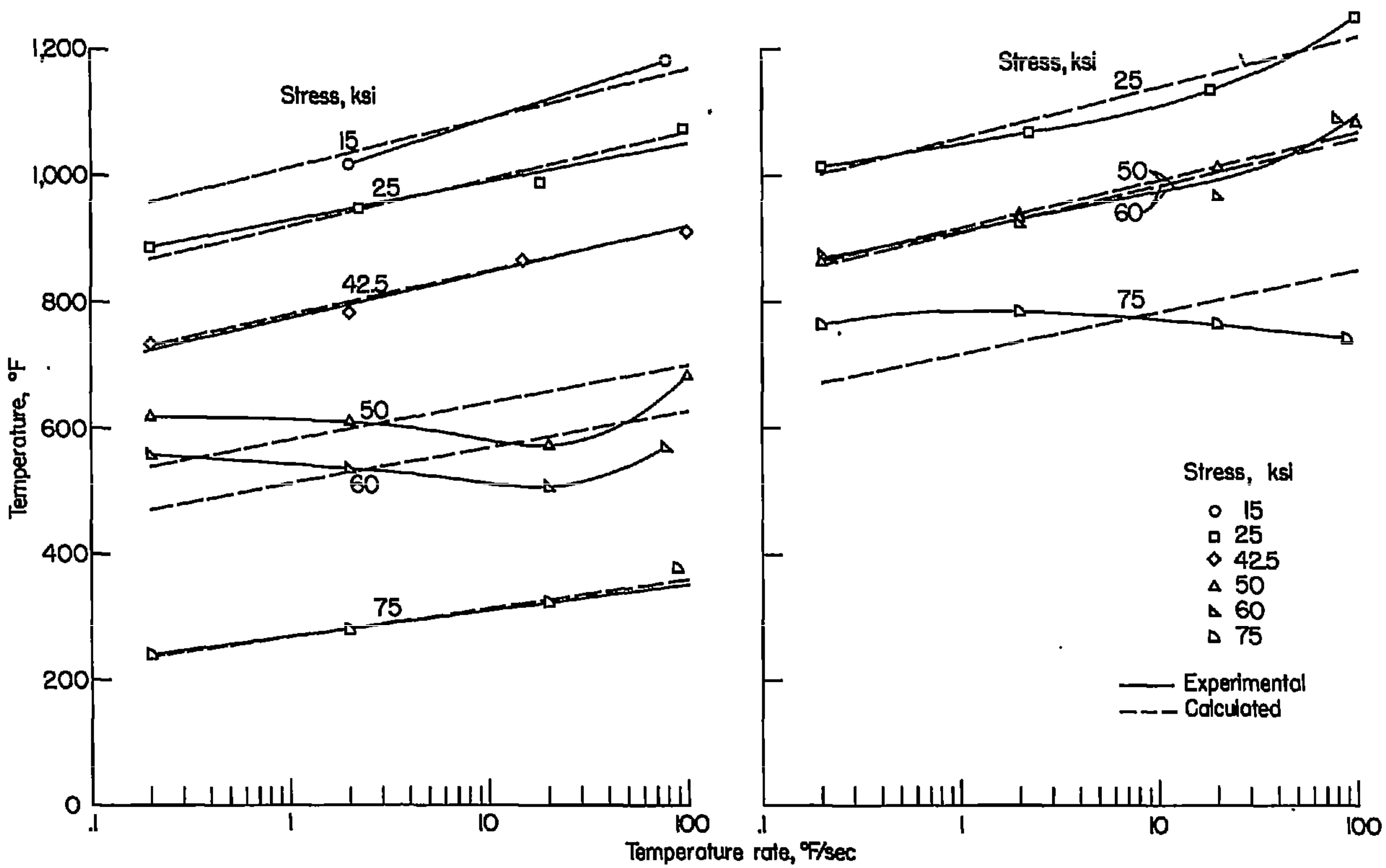


Figure 11.- Strain-temperature histories of RS-120 titanium-alloy sheet for temperature rates from 0.2° F to 100° F per second for various stresses.



(a) Yield.

(b) Rupture.

Figure 12.- Experimental and calculated yield and rupture temperatures for RS-120 titanium-alloy sheet for temperature rates from 0.2° F to 100° F per second for various stresses.

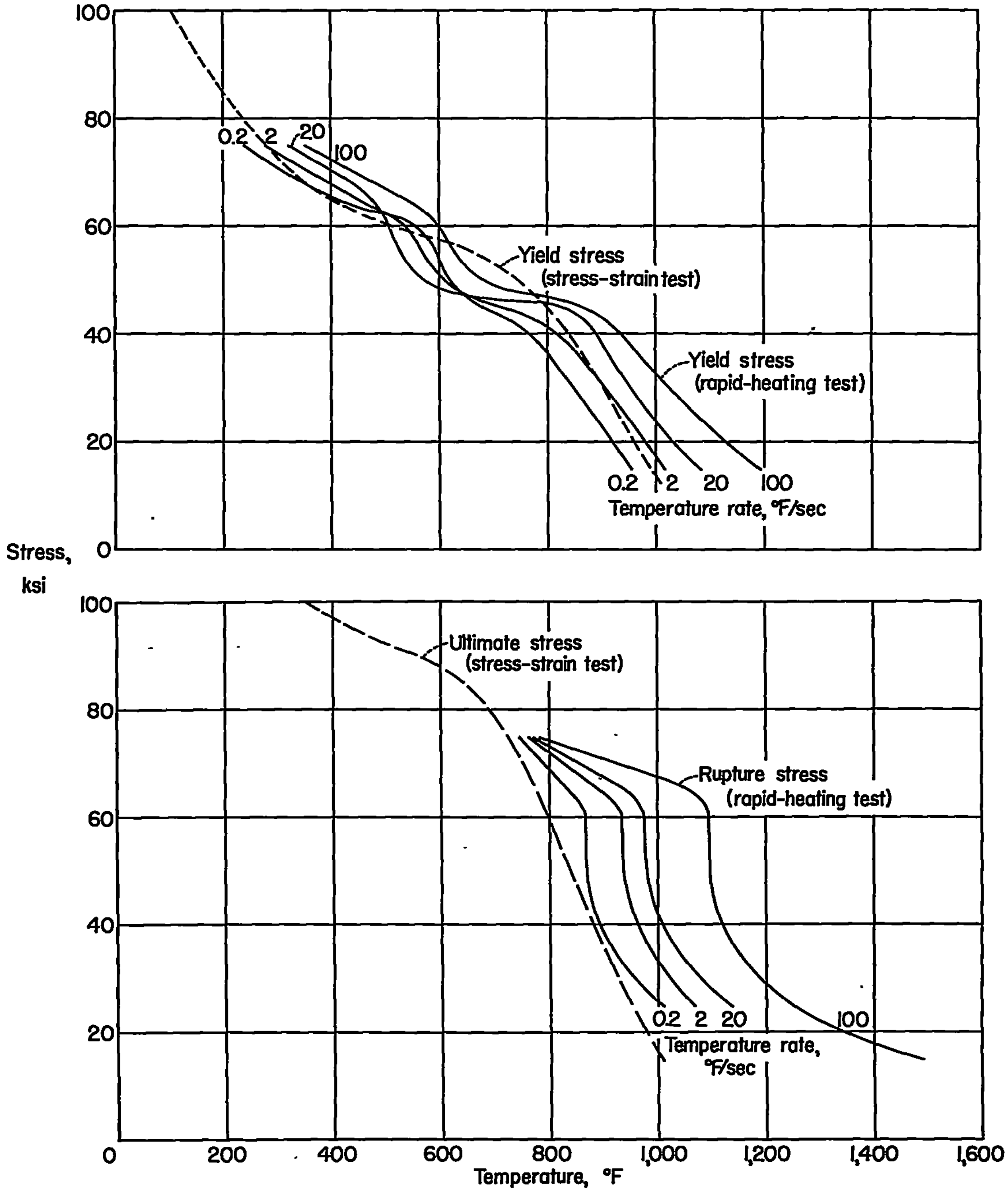


Figure 13.- Tensile yield and rupture stresses of RS-120 titanium-alloy sheet for rapid-heating tests from 0.2° F to 100° F per second and tensile yield and ultimate stresses for stress-strain tests after 1/2-hour exposure for a strain rate of 0.002 per minute.

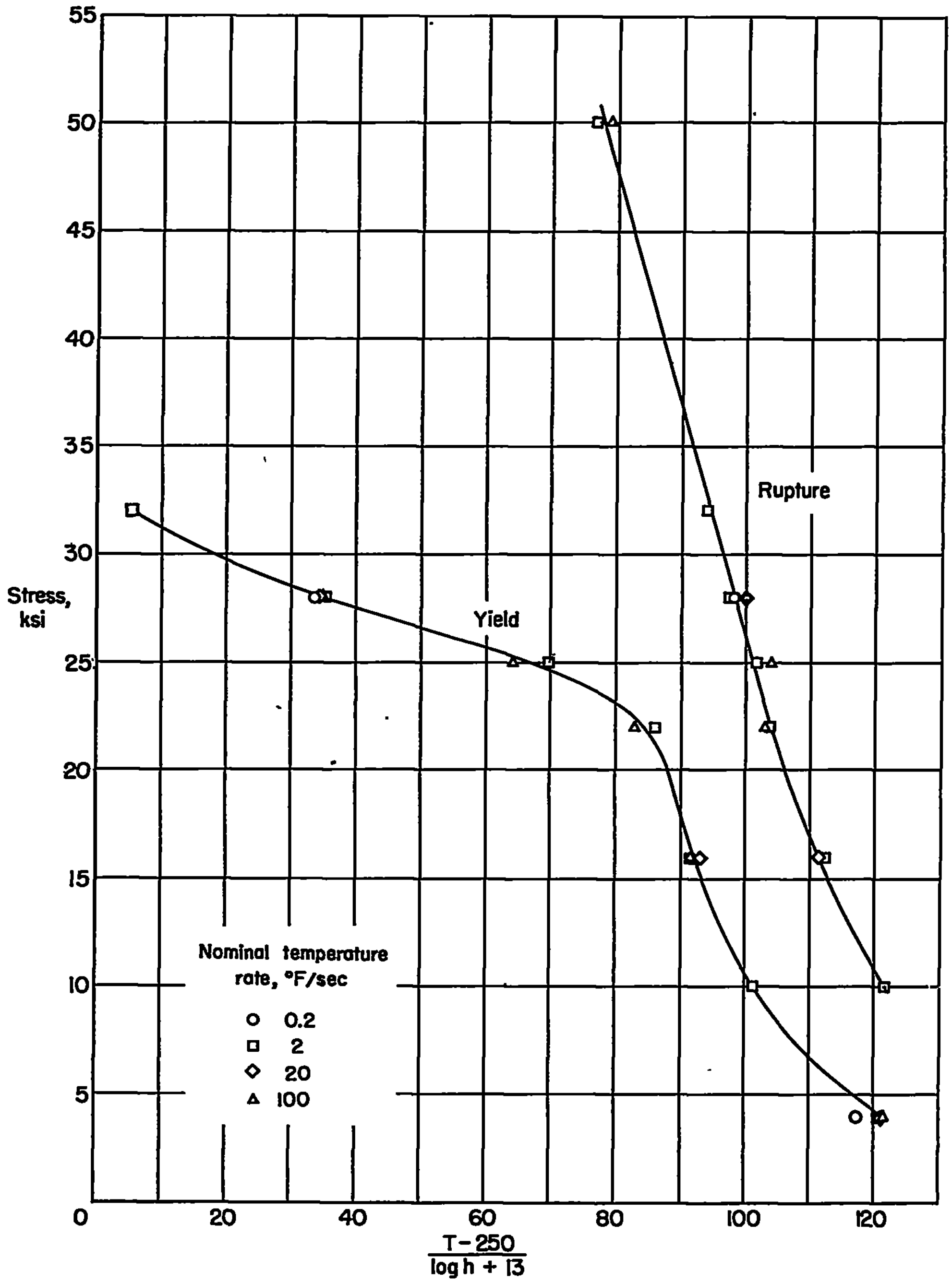


Figure 14.- Master yield- and rupture-stress curves for Inconel sheet using the temperature-rate parameter $\frac{T - 250}{\log h + 13}$. ($T$ is in °F and h is in °F per second.)

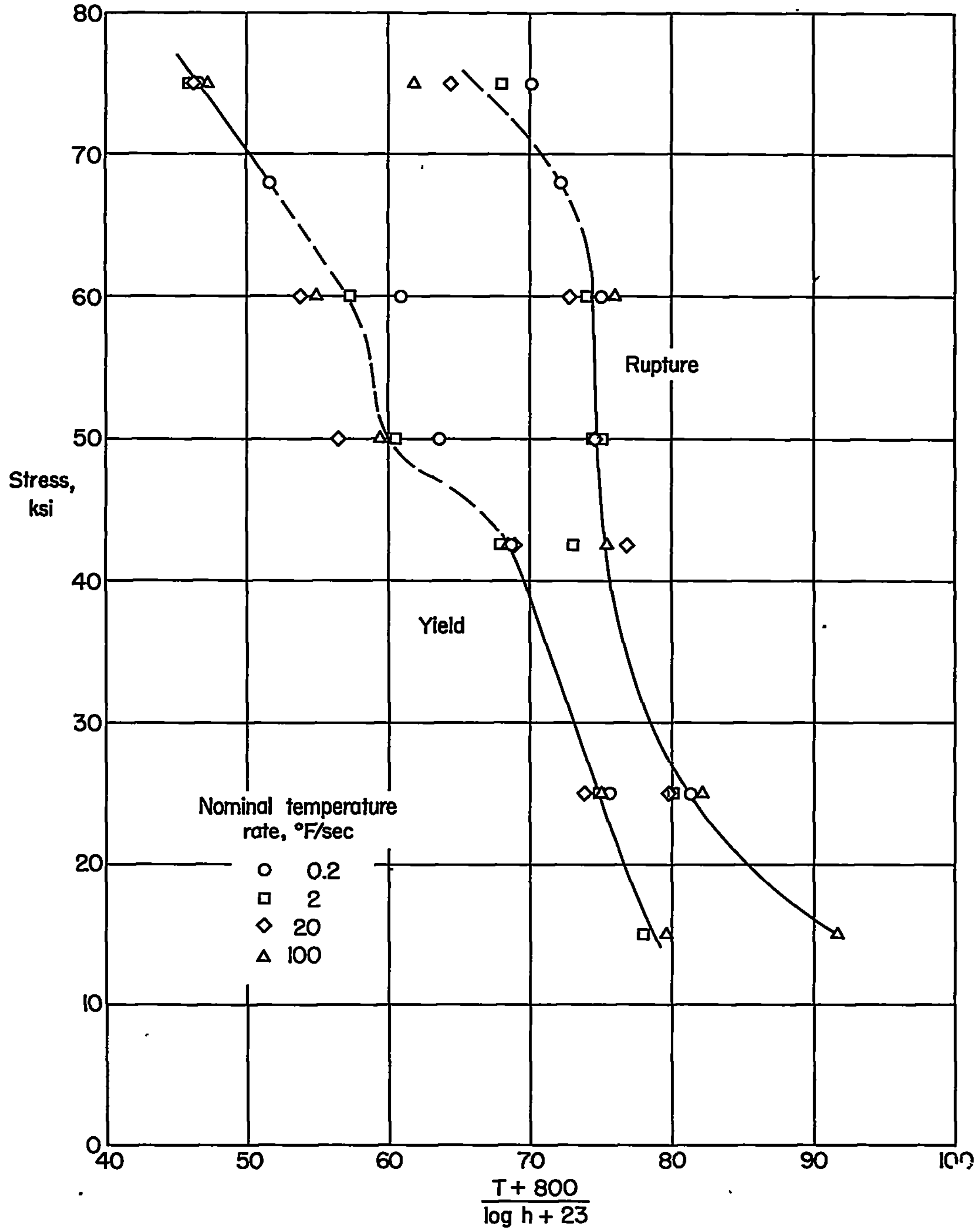


Figure 15.- Master yield- and rupture-stress curves for RS-120 titanium-alloy sheet using the temperature-rate parameter $\frac{T + 800}{\log h + 23}$. ($T$ is in °F and h is in °F per second.)